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Finite element analysis of mini implant biomechanics on peri-implant bone

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Abstract

Mini dental implant whose diameter is between 1.8 and 2.4 mm is a dental implant design currently implemented as bone screw in in orthodontics, as support for denture, and in situations when smaller diameter implant is the feasible option. Biomechanics of the peri-implant bone inserted by mini dental implant is of interest in this study where relevant studies are lacking. This study was intended to investigate using finite element analysis the induced stress and strain on peri-implant bone when a mini dental implant is loaded. The thread pitch of the mini dental implant and the peri-implant bone type were varied, with a constant loading (100 MPa pressure) applied on the mini implant. First, the mini dental implant with three different thread pitches (0.5 mm, 1.0 mm and 1.5 mm) were inserted into a type II bone. It was found that the higher the thread pitch, the higher the maximum stress (increased from 53.2 to 78.6 MPa) and the less distributed the stress on the peri-implant bone. Next is a mini dental implant with 1.0 mm thread pitch was inserted into peri-implant bone types II, III and IV. When the bone type changes from II to III, the maximum stress becomes lower (from 57.8 to be 51.7 MPa) but more high stress was distributed in the cortical bone. The strain was more than doubled (from 0.82 to be 1.76%) on the cancellous bone. When the bone type changes from III to IV, the maximum stress was doubled (from 51.7 to be 104.8 MPa) and more high stress was distributed over the cortical bone. In cancellous bone, the maximum stress was lower (from 9.1 to be 5.3 MPa), but the strain increases almost three folds (from 1.76 to be 5.07%).

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1. Introduction

Dental implants are accepted as one of the safe and successful dental restoration techniques. Typically, dental implant has screw like feature to facilitate insertion and to act as structure to transfer mastication loading into peri-implant bone. Various designs of dental implant have been introduced by manufacturers to cater the varying types and conditions of patient's jaw bone at different level of ages intended to ensure the implantation to be successful.

Mini dental implant is among the many dental implant designs introduced and currently implemented. Historically, mini implants have been used from few decades ago as small sized bone screws as anchors for the elastics in orthodontics which usually are inserted and remain in place for six to nine months [1]. The small sized bone screws were also used as temporary implant which is placed to support a denture during healing time [2]. Currently, mini dental implant is a type of dental implant when its diameter falls between the range of 1.8 to 2.4 mm [2-5].

Mini dental implant is used on patients who experience clinical situations or circumstances that make the smaller diameter implant as the most feasible choice. Some considerations which might lead to the selection of mini dental implant include the quality of the jaw support, bone width, issues on surface stress distribution at the foundation, adequacy of retention, stability of the implant, and muscular and occlusal balance [6]. Researchers mentioned that since mini implant is small in diameter, it is relatively inexpensive, simpler and less time consuming in installation, causes minimal bleeding, needs short healing time, minimises or even avoids the needed surgical procedures, and is easy to be inserted and removed [5-12].

Mini dental implants are available in various designs, among which the thread pitch, surface area, and length are varied. Implant design is a contributing factor to the success of implantation [13, 14]. The design directly affects the biomechanics of the peri-implant bone. Theoretically, by investigating the stress and strain magnitude and distribution in the peri-implant bone when a loading is applied on the dental implant, it can be determined whether the mini dental implant is safe to be used. Since clinical or experimental investigation on stress and strain on peri-implant bone is very difficult, very few investigations have been carried out. Instead, researchers use finite element analysis for this purpose. An example is a report by Handa et al. [7] who performed impact analysis on different thread pitch of the same implant design. They reported that different pitch results in different stress, with the lowest thread pitch produced lowest stress magnitude and vice versa. Another study carried out by Choi et al. [8] who varied the head length of mini implant reported that the stress increased with increasing head length. It should be noted that these examples used finite element analysis for getting the stress and strain on the dental implant. We have identified that the work on peri-implant bone biomechanics due to loading on mini dental implant is not yet available. Hence, this study on mini dental implant is undertaken to investigate the induced stress and strain on peri-implant bone when the implant is loaded. The thread pitch of the dental implant is varied. The investigation considers the difference in bone types (II, III, and IV).

2. Methodology

The mini dental implant and the peri-implant bone were modelled geometrically in 3D and were numerically analysed using commercial finite element software (Abaqus, Dassault Systèmes). The implant geometry was derived from a model used in previous works [15, 16]. The implant diameter is 2.2 mm which suits the category of mini implant [2-5]. Three designs with different thread pitch of 0.5 mm, 1.0 mm and 1.5 mm were produced (Fig. 1). The selection of thread pitches was as suggested by previous work on mini dental implant by Handa et al. [7].

For the peri-implant bone, previous model of molar teeth by the authors [17] was used (Fig. 2). The modelled peri-implant bone consists of cortical and cancellous bones where there is a transition area which lies beyond the outermost of the implant (0.5 mm from implant's inner diameter). The transition zone is supposed to be used for representing osseointegration condition (0 to 100%). In this study, the osseointegration is assumed to be 100% for simplicity. For representing bone types II, III, and IV according to Lekholm and Zarb [18] which are based on the thickness of cortical bone and the density of cancellous bone (Table 1), the geometry of the peri-implant bone is modelled accordingly. The material properties for bone types II, III and IV in this study were assigned from O'Mahony et al. [19] as listed in Table 2, with E is Young's modulus, G shear modulus and υ_{ij} is the Poisson's ratio for strain in i and j direction. Titanium was the material of the mini dental implant, with 110 GPa Young's modulus and 0.35 Poisson's ratio.

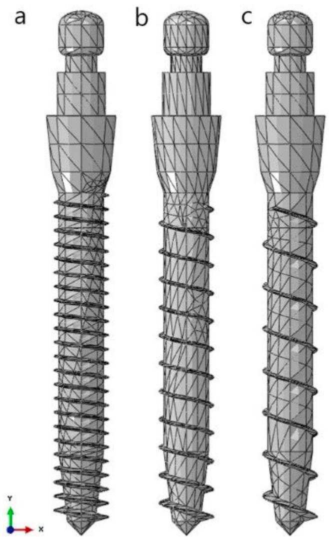

Fig. 1. Mini implant model with different thread pitch of (a) 0.5 mm; (b) 1.0 mm; (c) 1.5 mm.

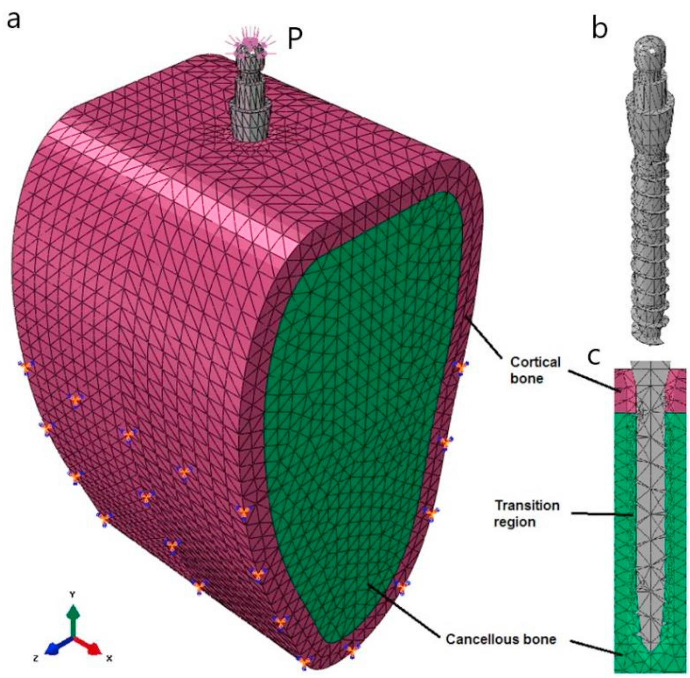

Fig. 2. (a) The modelled peri-implant bone with dental implant attached, applied with load (P) and boundary conditions; (b) mini implant model; (c) cross-section of the peri-implant bone.

Table 1. Bone type according to cancellous bone density and cortical bone thickness [18].

Bone type	Cancellous bone density	Cortical bone thickness
II	High density	2 mm
III	High density	1 mm
IV	Low density	1 mm

Table 2 Material properties for the transversely isotropic bone at 100% osseointegration conditions [19].

Properties	High density cancellous bone	Low density cancellous bone	Cortical bone
	100%	100%	100%
$E_{x\ (MPa)}$	1148	230	12600
$E_{y\ (MPa)}$	210	42	12600
$E_{x\ (MPa)}$	1148	230	19400
υ_{xy}	0.05	0.05	0.3
υ_{xz}	0.32	0.32	0.253
υ_{yz}	0.01	0.01	0.253
$G_{xy\ (MPa)}$	68	14	4850
$G_{xz\ (MPa)}$	434	87	5700
$G_{yz\ (MPa)}$	68	14	5700

There are two sets of simulations carried out in this study. First, the mini dental implant with three different thread pitches (0.5 mm, 1.0 mm and 1.5 mm) were inserted into bone type II. The next set is a mini dental implant with 1.0 mm thread pitch was inserted into bone types II, III and IV. For both sets, the implant was loaded with 100 MPa pressure on top of the implant. There are many ways to apply loading conditions on the implant but in this study, the direct external vertical load of 100 MPa was used to represent the occlusal load.

The assembled implant and peri-implant bone was meshed using tetrahedron elements. At the transition region adjacent to the outer surface of the implant, the mesh was refined while for other regions, the mesh was set at default size. This technique is expected to save the computation time without compromising the precision of the results. The contact type between the implant and the peri-implant bone was perfect merge. For this type of contact, the nodes in the transition area of both implant and peri-implant bone surface are commonly shared.

3. Results and Discussion

The finite element analysis to simulate the condition of the peri-implant bone when mini dental implant implantation is inserted, and a static load was applied has been successfully carried out and results were obtained as intended. The results from the first set of simulation, in which mini dental implant with three different thread pitches (0.5 mm, 1.0 mm and 1.5 mm) was inserted into bone type II and loaded, can be seen in Fig. 3 and Table 3. The stress distribution along the peri-implant bone is shown in Fig. 3. For ease of observation, the implant is not shown and only three quarter of the bone is revealed. As for the magnitude of stress and strain, the results of the highest stress and strain are as stated in Table 3.

Table 3. Maximum stress and strain induced on peri-implant bone type II with loaded mini dental implant having different thread pitch.

Thread pitch (mm)	Maximum stress		Maximum strain	
	Cortical bone (MPa)	Cancellous bone (MPa)	Cortical bone (%)	Cancellous bone (%)
0.5	53.2	8.1	0.13	0.63
1.0	57.8	4.0	0.20	0.82
1.5	78.6	4.4	0.30	0.65

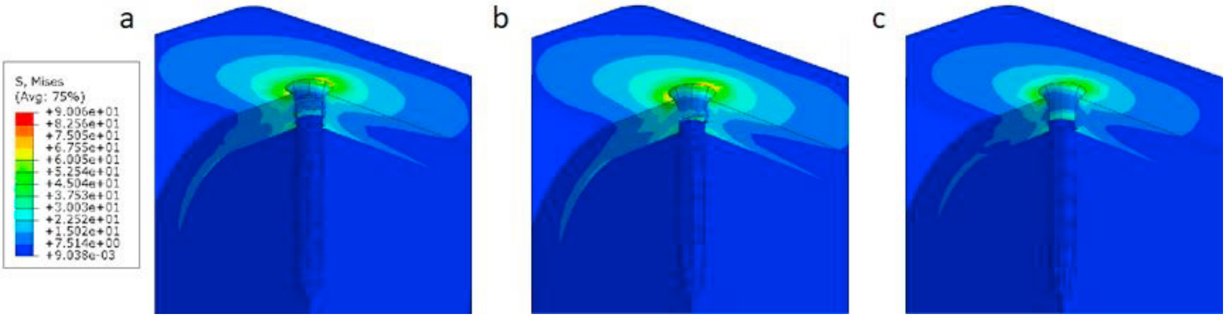

Fig. 3. Stress distribution on peri-implant bone of type II, shown here without the implant, for implant with (a) 0.5 mm; (b) 1.0 mm; (c) 1.5mm thread pitch.

In terms of stress, the highest stress on cortical bone of 78.6 MPa was induced by the implant with the highest thread pitch of 1.5 mm. The induced stress from the implant was distributed less to the surrounding jaw bone, or more focused to the peri-implant bone area adjacent to the implant. On the other hand, the implant with the lowest thread pitch of 0.5 mm results in the lowest stress magnitude on the cortical bone at 53.2 MPa. This implant also induced the highest stress on cancellous bone at 8.1 MPa. The stress was distributed more to the surrounding peri-implant bone. For implant with 1.0 mm thread pitch, the maximum induced stress on cortical bone was higher than the stress induced by 0.5 mm implant and the maximum induced stress on cancellous bone was about similar with the stress induced by implant with 1.5 mm thread pitch.

Generally, it can be said that the higher the thread pitch of a mini implant, the higher the maximum induced stress on the peri-implant bone. This agrees with previous work on mini dental implant by Handa et al. [7] which also varied the thread pitch. The difference in induced stress is suggested to come from the difference in surface area of the implant. This current study adds that lower thread pitch distributed the stress more evenly to the peri-implant bone. This is evidenced by the wider region of induced stress and the lower maximum stress on cortical bone. For implant with 0.5 mm thread pitch, the stress distribution is even better because it reaches the cancellous bone, evidenced by the higher maximum stress at cancellous bone.

In terms of strain, there was very small difference between the induced strains by the mini dental implant with different thread pitches. The small difference in induced strain happens on both cortical and cancellous bones.

Comparing the current study on mini implant with previous work by the authors on conventional sized implant [17,20], it is interesting to note that the induced stress and strain on peri-implant bone were lower for the former. This difference can be due to various factors, for example the overall surface area, the thread pitch, the shape of the implant's neck, and other geometry differences. Another note is that when taking into account the maximum yield stress and strain of cortical and cancellous bones [17], the stress and strain induced by the mini dental implant with three different thread pitches is still safe or below the allowable stress and strain.

The next set of simulation is where the mini dental implant with 1.0 mm thread pitch was inserted into peri-implant bone types II, III, and IV. The stress distribution on the peri-implant bone is shown in Fig. 4 and the maximum stress and strain on cortical and cancellous bones are shown in Table 4.

When the bone type changes from bone type II to bone type III which has thinner cortical bone, the maximum stress was lower (to 51.7 MPa), but more high stress was distributed in the cortical bone. Also, more stress was distributed to the cancellous bone, shown by the increase in maximum stress induced in cancellous bone, to be 9.1 MPa. The higher stress on cortical bone for bone type III causes the higher strain (of 1.76 %), which is double than for bone type II.

When the bone type changes from bone type III to type IV which has similar cortical bone but lower density cancellous bone, the maximum stress was doubled to 104.8 MPa, occurring at cortical bone. More high stress was also distributed over the cortical bone. In cancellous bone, the maximum stress was lower, but it seems it was less evenly distributed, causing the high strain of 5.07% (increase of almost three folds compared to bone type III).

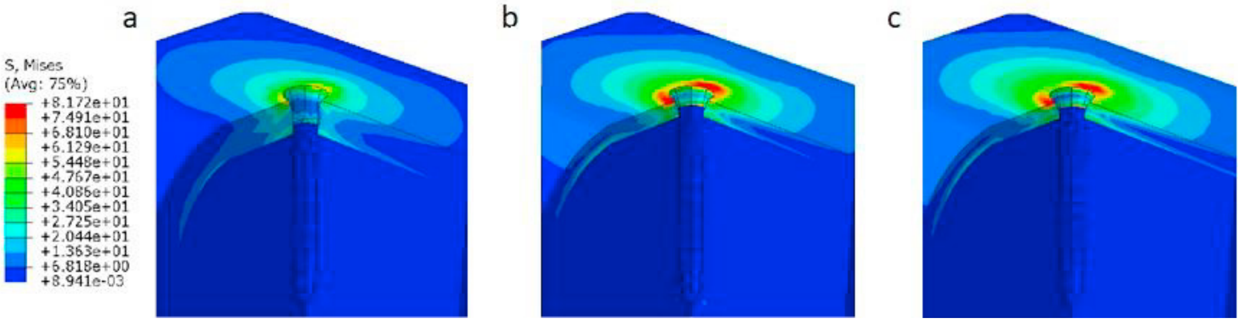

Fig. 4. Stress distribution on different jaw bone, shown here without the implant which has 1.0 mm pitch; (a) bone type II; (b) bone type III; (c) bone type IV.

Table 4. Maximum stress and strain induced on different peri-implant bone type with loaded mini dental implant having 1.0 mm thread pitch.

Bone type	Maximum stress		Maximum strain	
	Cortical bone (MPa)	Cancellous bone (MPa)	Cortical bone (%)	Cancellous bone (%)
II	57.8	4.0	0.20	0.82
III	51.7	9.1	0.23	1.76
IV	104.8	5.3	0.48	5.07

When the bone type changes from bone type II to bone type III which has thinner cortical bone, the maximum stress was lower (to 51.7 MPa), but more high stress was distributed in the cortical bone. Also, more stress was distributed to the cancellous bone, shown by the increase in maximum stress induced in cancellous bone, to be 9.1 MPa. The higher stress on cortical bone for bone type III causes the higher strain (of 1.76 %), which is double than for bone type II.

When the bone type changes from bone type III to type IV which has similar cortical bone but lower density cancellous bone, the maximum stress was doubled to 104.8 MPa, occurring at cortical bone. More high stress was also distributed over the cortical bone. In cancellous bone, the maximum stress was lower, but it seems it was less evenly distributed, causing the high strain of 5.07% (increase of almost three folds compared to bone type III).

There is very limited report on finite element analysis of peri-implant bone for different bone type to compare the results with. Previous work by the authors using conventional implant [17] reported higher induced stress and strain on peri-implant cortical bone compared to the current study. There were differences in stress and strain for cancellous bone. But then again, there can be various factors which cause this, including the difference in shape and geometry. Additional note from this current study is related to the maximum stress and strain with regard to the maximum yield stress and strain of cortical and cancellous bones [17]. The stress and as strain induced by the mini dental implant in this study with three different bone types are still within the safe region.

4. Conclusions

This study on mini dental implant was intended to investigate the induced stress and strain on peri-implant bone when the implant is loaded. Finite element analysis was performed for this purpose. The study varied the pitch thread of the mini dental implant (0.5 mm, 1.0 mm, and 1.5 mm), with the analysis done on bone type II. It was concluded that the higher the thread pitch of a mini dental implant, the higher the maximum induced stress on the peri-implant bone. It was also found that mini dental implant with lower thread pitch distributed the stress more evenly to the peri-implant bone. In terms of strain, there was very small difference between the induced strain by the mini dental implant with different thread pitches. For the next set done to investigate the difference in stress and strain shown by various bone types (II, III, and IV) with the bone implant having 1.0 mm thread pitch, it can be concluded that when the bone type changes from bone type II to bone type III, the maximum stress becomes lower but more high stress was distributed in the cortical bone. The change from bone type II to bone type III also causes the higher strain (of more than double) on the cancellous bone. When the bone type changes from bone type III to bone type IV, the maximum stress was doubled, and more high stress was distributed over the cortical bone. In cancellous bone, the maximum stress was lower, but the strain increases almost three folds compared to bone type III. Overall, the stress and as strain induced by the mini dental implant in this study with three different thread pitches and bone types are still within the safe region for the peri-implant bone.

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